Carderock Division
Naval Surface Warfare Center
West Bethesda, MD 20817-5700

NSWCCD-65-TR–2003/09 April 2003

Survivability, Structures And Materials Directorate

Technical Report

Long-Term Health Monitoring of the Composite Road Bridge on Delaware Route 896 – 2002 Update

by

Colin P. Ratcliffe
United States Naval Academy

Roger M. Crane
NSWC, Carderock Division

NSWCCD-65-TR–2003/09 Long-Term Health Monitoring of the Composite Road Bridge on Delaware Route 896 – 2002 Update

DEPARTMENT OF THE NAVY
NAVAL SURFACE WARFARE CENTER, CARDEROCK DIVISION
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From: Commander, Naval Surface Warfare Center, Carderock Division
To: Chief of Naval Research (ONR 332)

Subj: COLLABORATIVE STRUCTURAL EVALUATION OF A HIGHWAY COMPOSITE DECK BRIDGE

Ref: (a) Program Element 0602234N, Seaborne Structures Materials Program

Encl: (1) NSWCCD-65-TR–2003/09, *Long-Term Health Monitoring of the Composite Road Bridge on Delaware Route 896– 2002 Update*

1. Reference (a) requested the Naval Surface Warfare Center, Carderock Division (NSWCCD) to perform an ongoing investigation into using broadband vibration data to monitor the structural integrity and health of an all-composite road bridge. Enclosure (1) contains the vibration data which were obtained for the year 2002 (the fourth consecutive year) as part of an effort to continue to develop a vibration-based, non-destructive evaluation method suitable for long-term inspection of composite structures. The report covers the 2002 data collection on an all-composite bridge and compares the modal results with those obtained from previous years.

2. Comments or questions may be referred to Dr. Roger M. Crane, Code 655; telephone (301) 227-5126; e-mail, Roger.Crane@navy.mil.

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Subj: COLLABORATIVE STRUCTURAL EVALUATION OF A HIGHWAY COMPOSITE DECK BRIDGE

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Enclosure (1)

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14. ABSTRACT
This report presents the results of an ongoing investigation into using broadband vibration data to monitor the structural integrity and health of a composite road bridge. The bridge deck configuration is of sandwich construction, as are the Joint Modular Lighter System (JMLS) and the LPD-17 mast, which are currently under development by the U.S. Navy. Demonstrating the ability to determine the structural health and any degradation which causes a change in the stiffness of the Route 896 bridge in its service environment would illustrate the utility of the broadband vibration technique for Navy structures. The primary development being reported here is the ability to determine changes in the structural integrity of the bridge from the first inspection performed in 1999 compared with the state of the structure in 2002. This development will provide guidance for the locations that are showing changes in their structural integrity as the structure ages. This comparison is being performed using the Structural Integrity and Damage Evaluation Routine (SIDER) which is being developed to assist in the health monitoring of large structures.

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Administrative Information

The work described in this report was performed by the Structures and Composites Division of the Survivability, Structures, and Materials Department, at the Naval Surface Warfare Center, Carderock Division (NSWCCD), in conjunction with the United States Naval Academy. The work was funded by the Office of Naval Research, Code 332, under the Seaborne Structures Materials Program (PE 0602234N) under the guidance of Dr. Ignacio Perez.

Acknowledgements

The authors would like to acknowledge the support by the Delaware Department of Transportation (DelDOT) for the personnel to close the bridge so that the inspection could be performed and for providing the rowboat to allow for the underside inspection. In addition, the authors would like to thank the University of Delaware for their support in carrying out the bridge inspection.

Executive Summary

Composite materials are gaining increased use as a structural material for Navy applications. Some of the applications where composite materials are currently being used are for the masts for LPD-17-class ships, the Improved Navy Lighterage System (INLS), and the advanced sail for the *Virginia*-class submarines. With structures of this size, methodologies for determining structural integrity become very important. Although inspection techniques are available which can be readily implemented in a laboratory setting, few exist which can be used in the type of service environment to which the aforementioned applications are subjected. In addition, few can provide timely inspection for these large structures that have surface areas, which can be thousands of square feet.

This report presents the results of an ongoing investigation which uses broadband vibration data to monitor the structural integrity and health of an all-composite road bridge. More specifically, this report presents results of the fourth inspection of the bridge I-131 on Business Route 896 located in Glasgow, Delaware. The bridge consists of two E-Glass/vinyl ester sections (each section 13 ft x 32 ft) joined by a longitudinal joint in the traffic direction. Each section is a sandwich construction consisting of a 28-inch thick core and 0.5-0.6 inch thick facesheets. The bridge deck configuration is representative of the deck for the JMLS and the LPD-17 masts that are currently under construction. This fourth vibration inspection was performed to establish the changes occurring during the service life of this civil structure. Demonstrating the ability to determine the structural health and any degradation that results in a change in stiffness of the Route 896 bridge in its service environment would illustrate the utility of the broadband vibration technique for Navy structures.

Vibration data were obtained from a mesh of 1050 test points located in a regular array on the upper and lower surfaces of the bridge. The mesh used for this fourth inspection is the same as that used in the prior three inspections. (Reference 1) From the modal information and the visualization of the data, several aspects of the structural behavior of the bridge are reported and compared to the prior year's inspections. The primary development being reported herein is the ability to determine changes in the structural integrity of the bridge from the first inspection performed in 1999 compared with the state of the structure in 2002. This development provides guidance for the locations that are showing changes in their structural integrity as the structure ages. The comparison is being performed using the Structural Irregularity and Damage Evaluation Routine (SIDER) which is being developed to assist in the health monitoring of large structures (Reference 2). Demonstrating the ability to determine the structural health and any degradation in properties of the Route 896 bridge in its service environment potentially illustrates the utility of the broadband vibration technique for Navy structures.

In addition to presenting a comparison of the modal results with those obtained from previous years, this fourth report in the bridge inspection series also presents the latest developments in the SIDER test method which includes an improved algorithm and an improved method of presentation. This improved SIDER analysis is also conducted on the prior years testing information, and the results are presented herein. Since the SIDER analysis has been

substantially developed and modified since the third inspection effort on the bridge, this report details those changes. The SIDER results locate local variations in a structure, and how that variation is changing with time. This SIDER analysis is a further development to establish and create a vibration-based non-destructive evaluation method suitable for long-term inspection of large-scale composite naval structures.

Background

A research and educational collaboration initiated in the early 1990s by the University of Delaware Center for Composite Materials (CCM), the University of Delaware Department of Civil and Environmental Engineering (CEE), and the Delaware Transportation Institute (DTI) culminated in the installation of an all-composite bridge deck on Business Route 896 in Glasgow, Delaware. Other partners in the project were the Delaware Department of Transportation (DelDOT), the Federal Highway Administration (FHWA), and local industry and contractors including Hardcore Composites, Anholt Technologies, and James Julian, Inc.

The bridge is identified in the Delaware highway system as Bridge 1-351. It is situated at approximately 39^{o}36.63'N 75^{o}44.77'W and carries Route 896 over a small stream known locally as Muddy Run. During the vibration trial reported here, the Muddy Run water under the bridge was several inches deep at the sides, increasing to about 3 feet in the middle. The water level was comparable to the levels during the trials conducted in the previous three years.

Many details of the vibration analysis of this bridge are included in References 1, 3 and 4 (May 99, June 2000, August 2001 reports). The reader is directed to those references for more details on the experimental aspects of the vibration test and structural features of the bridge.

The new bridge was installed and opened to traffic on November 20, 1998. This bridge carries a single-lane one-way road. Figure 1 is a panorama of the bridge, compiled from several still images. In this picture, north is left and south is right.

Figure 1. Panoramic View of Composite Bridge Deck

The initial focus of the vibration trial was to obtain a large quantity of frequency-based vibration data from the bridge deck. The data were for analysis as well as archiving for later comparison. This report includes the results of the modal analysis, and a comparison with the previous modal results from 1999, 2000 and 2001. The results of applying the SIDER broadband damage detection method are also presented and discussed.

Key Personnel

The following were the key on-site personnel involved in this July 2002 vibration trial.

United States Naval Academy (USNA)

Professor Colin P. Ratcliffe

Naval Surface Warfare Center, Carderock Division (NSWCCD)

Dr. Roger M. Crane

The Center For Composite Manufacturing (CCM)

Professor John W. Gillespie, Jr.
Dr. Dirk Heider
Dr. Carl Krauthauser
Dr. Nick Shevchenko
Dr. Ken Yoon

Delaware Department of Transportation (DelDOT)

A team of employees closed the bridge, provided on site support such as supplying a boat, and provided safety numbers to ensure traffic did not pass the barricades.

Schedule

The following summarizes the experimental phase of the project.

Monday July 15, 2002

CCM personnel on site to check mesh markings remaining from the June 2001 trial. Mesh was measured and repainted where it was worn off.

Tuesday July 16, 2002

CCM personnel conduct SIDER testing of bridge.

0830 Bridge closed to traffic. Reinstalled accelerometers at same locations as for 2001, and run all cables. Prepared analyzer.

1000 Commenced data capture for impacting the underside of the bridge.

1730 Bridge reopened to traffic.

Wednesday July 17, 2002

0830 NSWCCD/USNA personnel arrived on site; started laying out cables.

0845 Bridge closed to traffic. Reinstalled accelerometers at same locations as for 2001, and ran all cables. Prepared analyzer.

0926 Commenced data capture for impacting the topside of the bridge.

1140 Topside data capture completed. 573 data files were recorded. This represents 4.23 measurements per minute, which compares to 3.72 measurements per minute in June 2000. The increase in speed is due to improved software and hardware.

1146 Commenced data capture for underside.

1312 Break for Lunch.

1328 Resumed testing of underside of bridge.

1436 Underside data capture completed. 512 data files were recorded for this phase. This represents 3.32 measurements per minute, which compares to 2.96 measurements per minute for June 2000.

1500 Bridge reopened to traffic. Departed for Maryland, started data translation en-route.

1545 While still on the road, SIDER results were generated, and provisional modal results from first three modes were available.

Bridge General Description and Test Setup

A more detailed description, including a survey of the bridge dimensions, is included in Reference 1. For this project, the bridge can be considered to have three main components; two guardrails, and one deck. Dynamically, these components are decoupled by rubber seals installed between each guardrail and the deck. The main components of the bridge are shown in Figures 2 through 4, which are copied from Reference 1. The deck is the main component of interest for this project. It is approximately 26 feet wide and 32 feet long, and sits on abutments at the north and south banks. The deck was manufactured in two parts, each approximately 32 feet long and 13 feet wide. The two parts are joined by a longitudinal north-south joint, which can be seen in Figure 4, which shows the under side of the bridge.

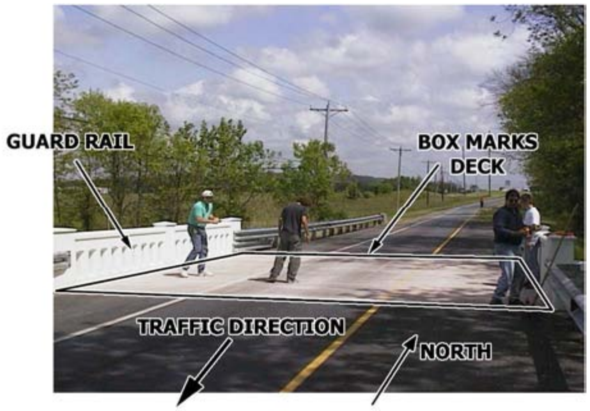


Figure 2. View of Bridge Deck Components (Top)

Figure 3. View of Bridge Deck Components (Side)

Figure 4. View of Underside of Composite Bridge Deck, Looking North with Centerline Joint

Survey

As part of the May 1999 trial, the bridge was surveyed. The global origin for all measurements was taken as the extreme southeast corner of the concrete guardrail at deck level; this being a point on the bridge unlikely to be damaged or moved by traffic or other accidents. The X-axis was parallel to the line of the bridge (pointing approximately north); the Y-axis was across the bridge (pointing approximately west); and the Z-axis pointed upwards. The axis origin was at the height of the top bridge deck. The small curvature of the deck surface was ignored so all test points on this surface were assigned zero Z-coordinate values. As a result of this origin location and ignoring the surface slope, all test points on the bottom surface had the same negative Z-coordinate value (-30 inches).

The Test Grid

The mesh of test grid points consists of two sub meshes; one on the top surface and one on the bottom surface. Both meshes were uniform, with an 18-inch spacing in the X-direction (north-south), and a 12-inch spacing in the Y-direction (east-west). This is the identical grid arrangement as used in May 1999, June 2000, and June 2001. The mesh was re-established in exactly the same way as in Reference 3, and thus the procedure and details are not repeated here.

Accelerometers

As for the three prior tests, four accelerometers were used to record the motion of the deck. The locations and installation method were identical to the information presented in Reference 3, and are not repeated here.

Equipment

The reader is directed to References 1 and 3 for details of the accelerometers, force gage and analyzer. The identical equipment and settings used in prior years were also used for this test.

Data Capture

Based on the successful experiences of the three prior trials, each coordinate was impacted two times, and the frequency response functions were frequency averaged. Care was taken to repeat the data capture for a particular coordinate if there was the slightest doubt as to data quality. Data were again captured in the frequency range 0-1 kHz, with a frequency resolution of 0.625 Hz and a real-time measurement of 1.6 seconds per impact. The exponential window was again set at 0.300 seconds.

The hammer input range was kept fixed at 1 Volt. The accelerometers, PCB ICP Type 353B33 with a nominal sensitivity of 100 mV/g, input ranges were predominantly 310 mV, with the range being increased to 1 Volt when overloads were detected. Auto rejection of overloaded signals was enabled throughout.

The data capture for both the upper and lower surfaces was completed in one day. The upper surface data were captured from 0926 to1140, giving 4.07 test points per minute. It should be noted that this capture rate is different from that provided in the schedule. This is because there was repeat testing of grid points and this latter value indicates the capture rate for the data retained for analysis. The lower surface data were captured from 1146 to 1436, giving 3.27 test points per minute. The speed for testing the entire bridge was comparable to the rate accomplished in 2001. This is indicative of a smooth operation conducted by an outstanding team.

Data Quality

Overall, the data obtained for this trial are of a remarkably high quality. In-field quality monitoring was predominantly assessed with the coherence function. Up to approximately 400 Hz the coherence function was typically at 98% or better, with virtually no drop-outs. As is expected for impact-generated data, there was a drop-out in excitation power (and hence coherence and data quality). The first drop-out was near 550 Hz. Because of this drop-out, the data above about 450 Hz have a higher signal noise than the data below 450 Hz. However, the high-frequency data quality is still acceptable for many applications.

Figure 5 shows the coherence functions averaged for all measurements and all accelerometers, compared with the average coherence for the May 1999, June 2000 and May 2001 trials. 100% coherence represents "perfect" data. Typically for large-scale vibration testing, anything over about 80% is deemed acceptable. As can be seen from Figure 5, overall, the data quality is very high.

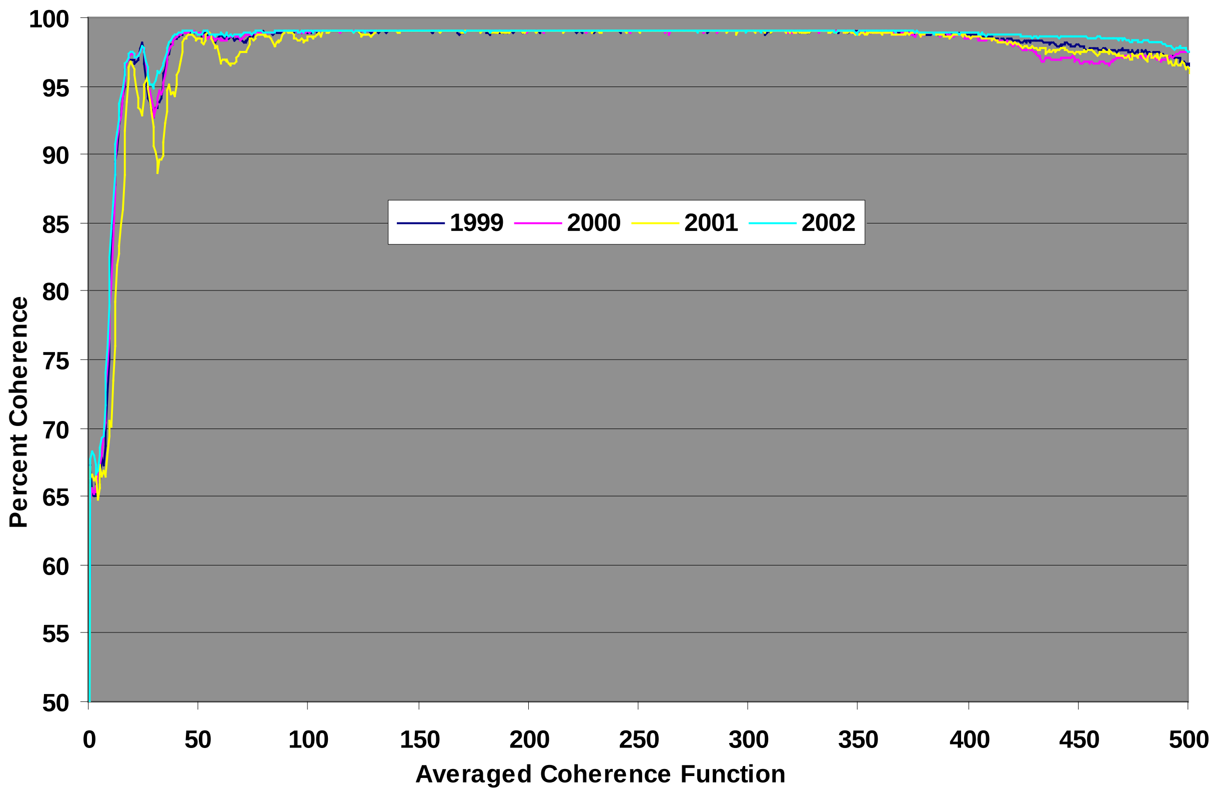


Figure 5. Average Coherence Function for the Four Years

Data Translation

The raw analyzer data files were converted to a proprietary, archive-suitable format using the data conversion module included as part of a suite of programs (Reference 5). This suite of programs is designed for large-scale experimental vibration testing and SIDER analysis. The archive-suitable files were then translated into a third file format. This final format is compatible with the commercial VES modal analysis suite supplied by Vibrant Technology, Inc., 1999 (Reference 6). Because of the way the modal analysis program operates on and changes the data files, this VES-compatible file format is less suitable for archiving and other uses.

Modal Analysis

Conventional modal analysis was conducted for prior years to determine the changes in the natural frequencies and damping loss factor. This type of analysis can provide an indication of degradation in structural properties. However, typically the amount of degradation that needs to occur in a structure for either the natural frequency or damping loss factor to show a statistically significant change is much greater than the changes that can be detected using the SIDER technique (Reference 7). As such, the natural frequencies and damping loss factors are not provided herein, with the exception of noting that there was no statistically significant change in the natural frequencies of the bridge.

Structural Irregularity and Damage Evaluation Routine (SIDER) Results

The SIDER procedure for locating structural irregularities and damage has been developed over the last few years, and is detailed in Reference 8. In the previous three inspections, the SIDER was used to produce two different types of summary plots: raw and statistically enhanced. It was seen in Reference 4 that the statistically enhanced plots provided the most informative means of presenting the data for ease of interpretation. The procedure has now been modified and the results using this new methodology for this year and all previous years are presented herein.

Part of the SIDER analysis algorithm requires a normalization procedure. This normalization had previously been done on the final results, where the rms value was arbitrarily set to 1. A statistical significance analysis was then performed on the SIDER values that were determined. This approach led to some false indications of structural irregularity or damage, and did not give a good comparative tool for ranking different parts of a structure. In the literature, it was seen that damage has a minimal effect on the vibration displacement shape. By modifying the SIDER algorithm to apply the normalization at the displacement shape part of the calculations, significant improvements and overall usefulness of the procedure were achieved. This is the methodology that was used to generate the results presented below. In order to make comparisons with previous years, the data from previous years were also reprocessed using the modified algorithm.

One additional variation separates the 2-D gap smoothing method used in the SIDER analysis into individual 1-D summaries. It was seen in other data processing performed for a ½-scale composite hull, that, by looking at the analysis results as two separate sets of results, one for each of the directional analyses, structural features that were normal to the analysis direction were more readily identified.

An additional enhancement which has been made to the SIDER interpretation is the data presentation. One aspect of the SIDER interpretation which needed improvement was the method of visualizing the regions of damage. The authors conducted an extensive survey of the industry to identify an improved means to present the results from the SIDER testing. The routine that appears to provide improved graphical interpretation of these results is presented in this report.

Figures 6 through 9 show the SIDER results for 1999 to 2002 using the new normalization procedure and visualization routine. Various anomalies are readily apparent. In the east-west analysis plots, there is a feature in the center of the figure, which appears in the results for each year. This actually corresponds to the center splice plate used to connect the two sandwich core sections together. In addition, there is a strong feature that appears to the right of center in these figures in all years. For the north-south analysis lines, there are some features on both sides of the figure. Another feature to point out is the large indication in the east-west analysis in Figure 6 near grid point –12, 20. It is seen that in subsequent years, figures 7-9, that this indication does not appear. Currently, there is no concern for this point, since it is the authors' belief that there may have been a data capture error at this grid point during the 1999 trial. Continued observations are necessary to verify whether this is a data error or indicates a structural change.

In both cases, these features have existed since the initial inspection. A more informative utility of the SIDER routine is to see how the structure is changing over time. These trend lines provide an indication on which feature is increasing in severity. Figure 10 shows the difference between years 1999 and 2002 using the east-west and north-south analysis directions. The results in this figure show the slope of the least squares best-fit line fitted to the SIDER values versus time, a separate line being fit for each grid point. Thus, a large value indicates an increasing SIDER trend, and zero indicates no trend (change) with time.

Figure 10 shows that there is really only one area of concern that has shown an increase in the damage index from 1999 to 2002. This feature runs north-south since the analysis that has been done uses the east-west lines. This feature is on the splice plate region and is still fairly localized. It will be important in subsequent inspections to visually examine this area to see if there is any noticeable defect.

It should be noted that to date, there is no established correlation between the SIDER values determined and the amount of structural degradation that has occurred.

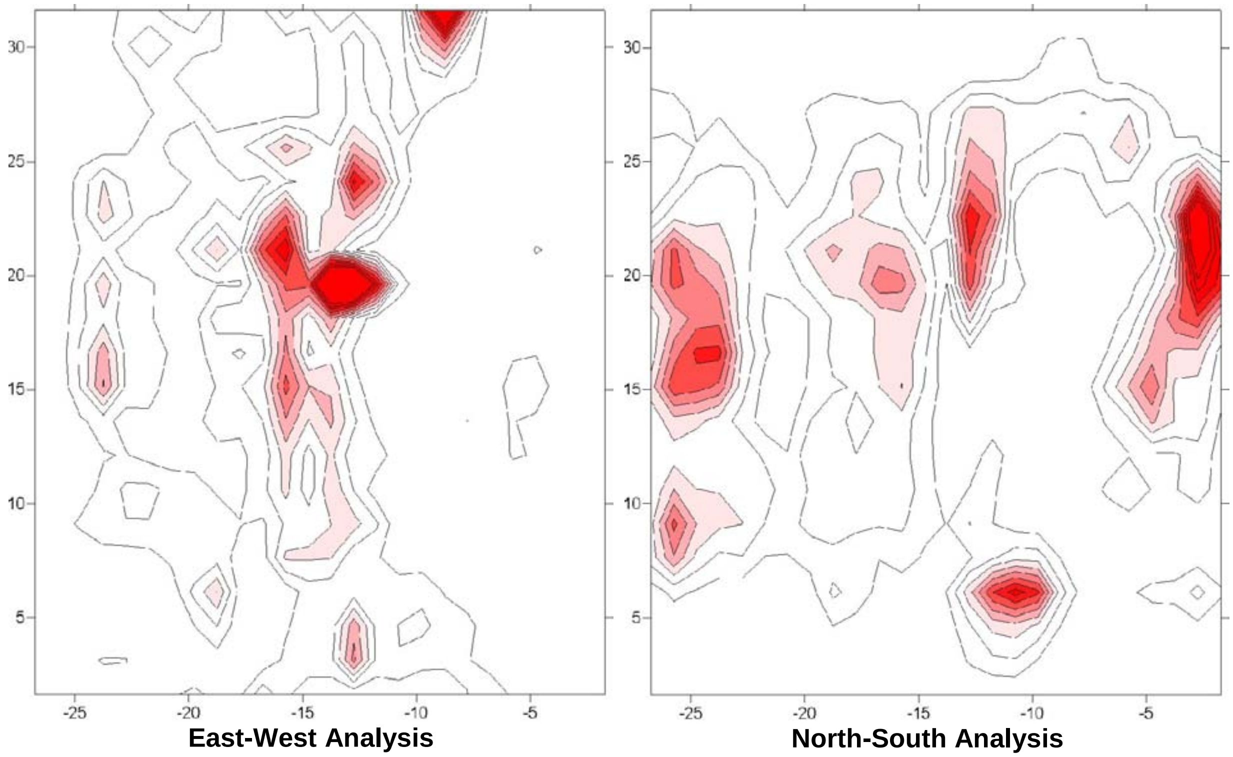


Figure 6. SIDER for 1999

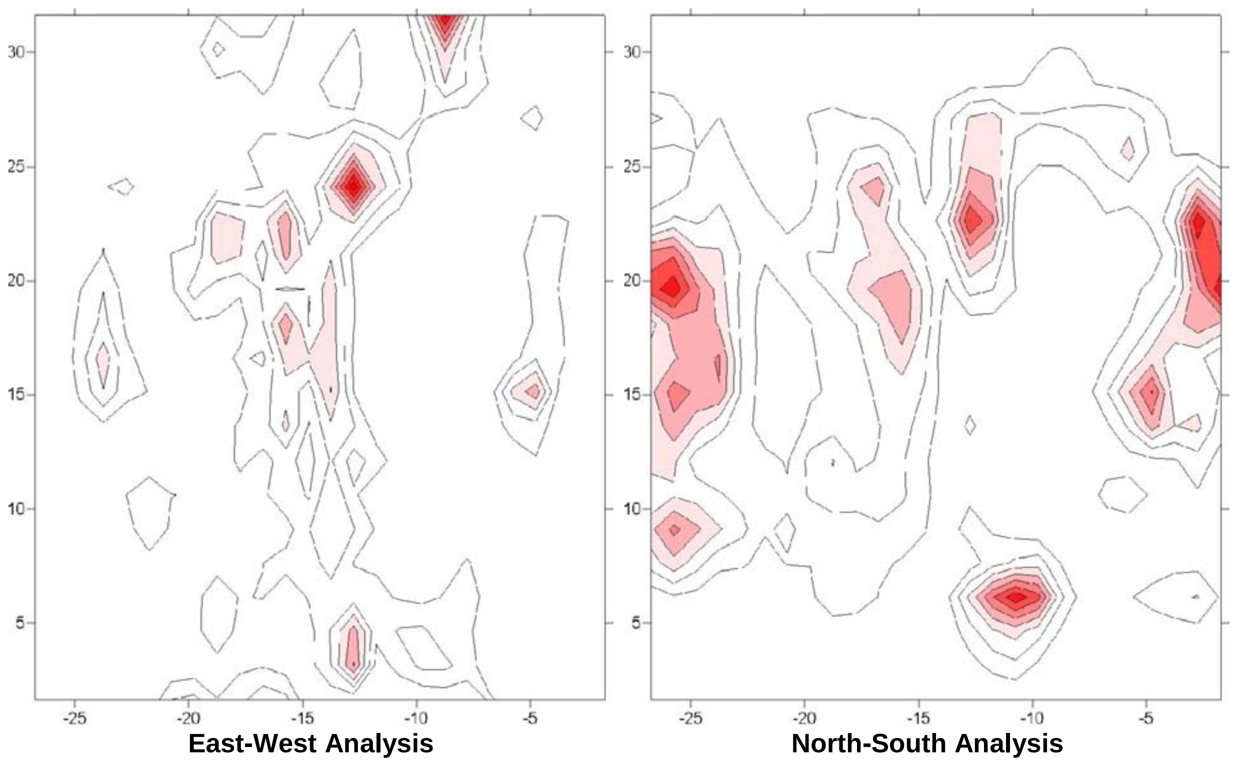
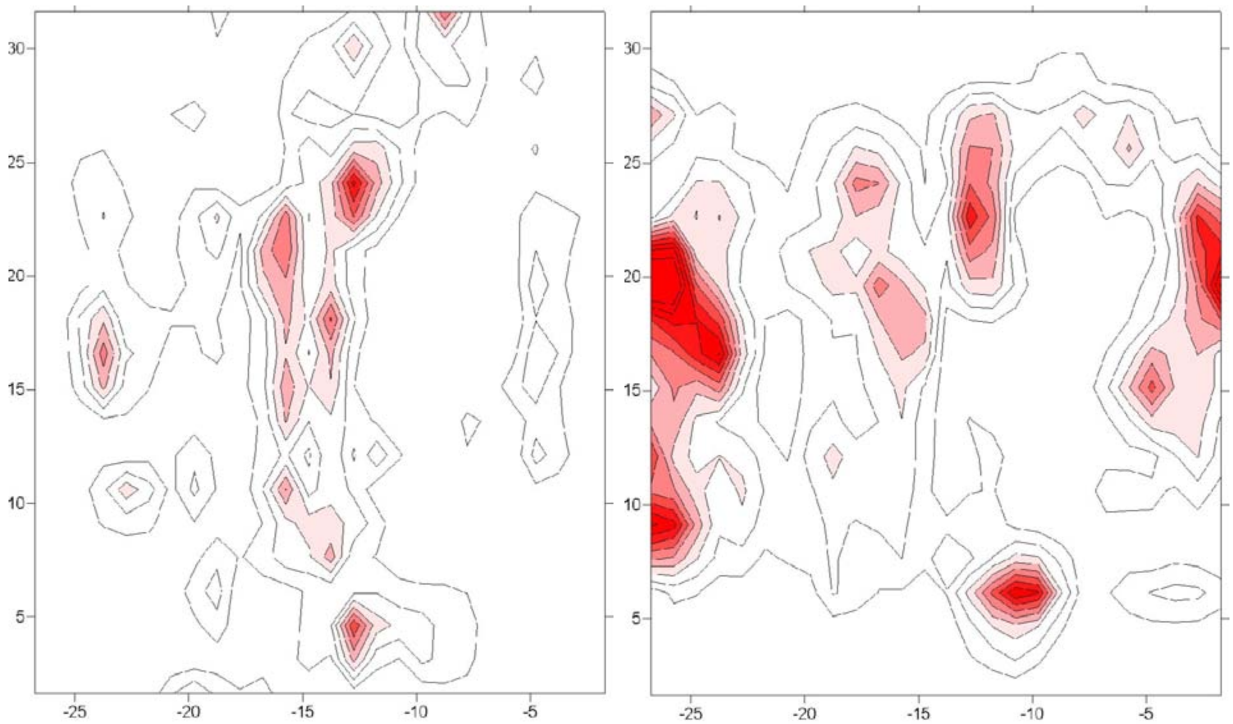
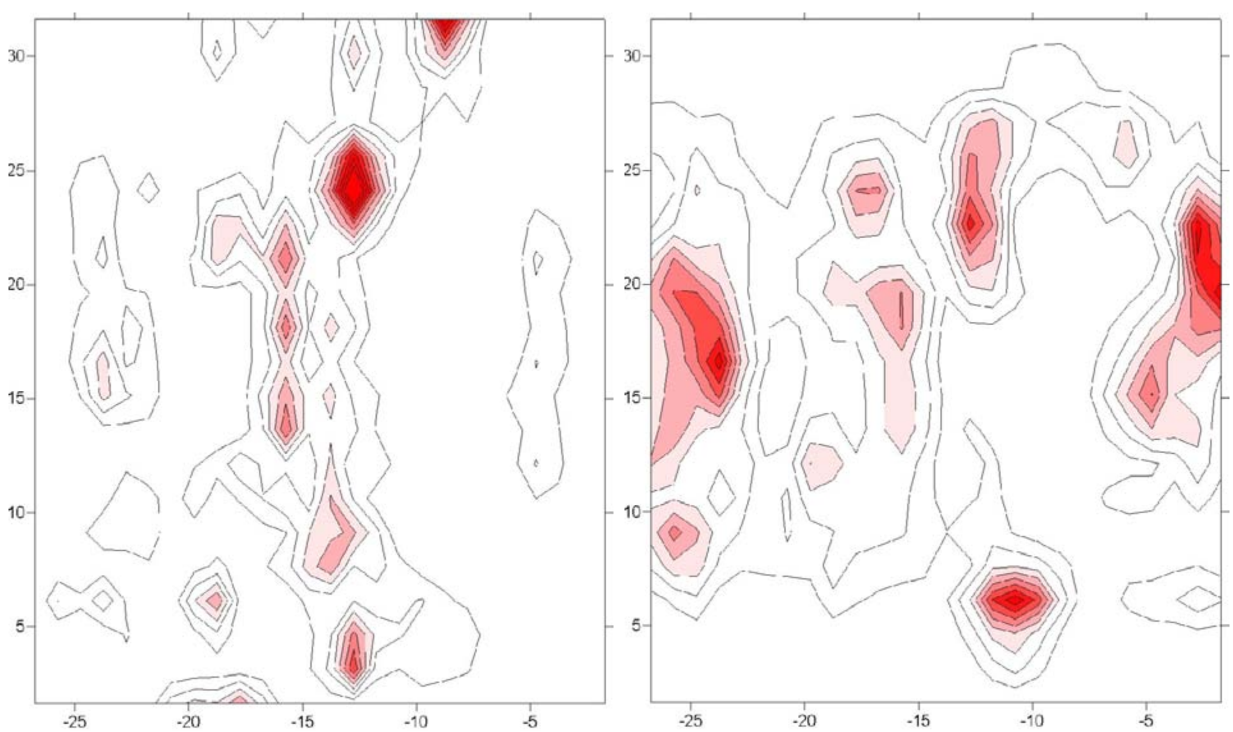


Figure 7. SIDER for 2000



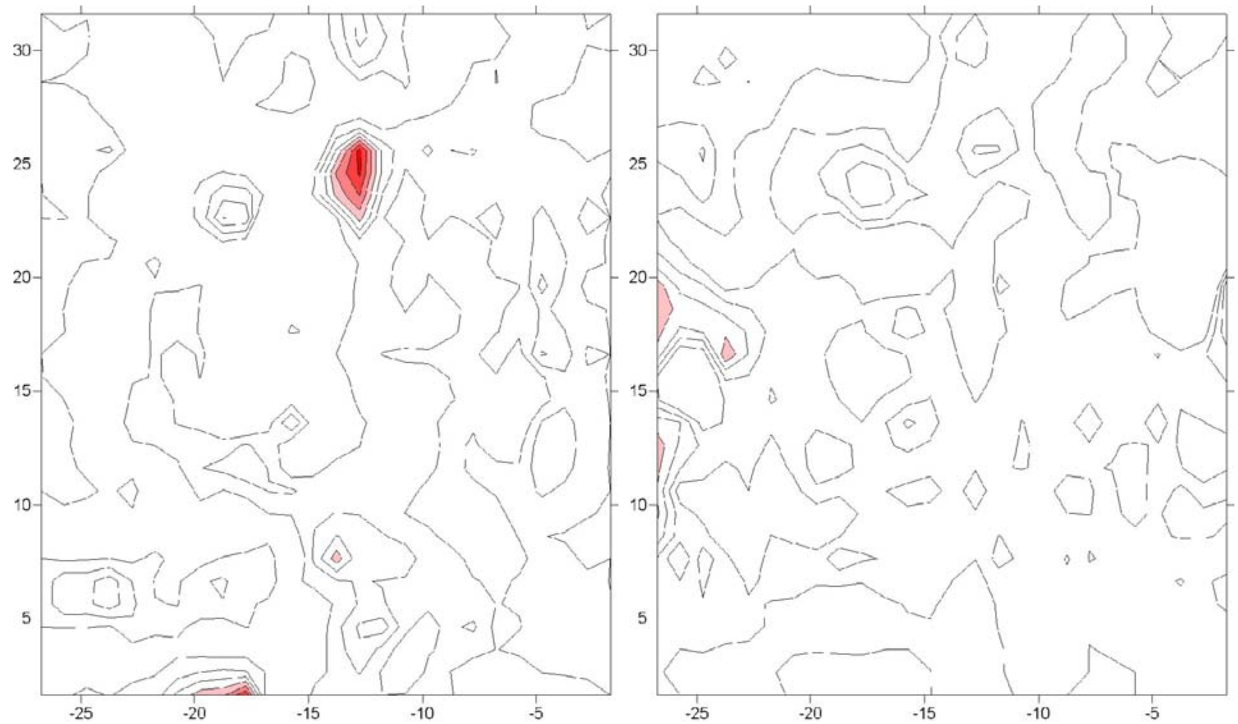
East-West Analysis **North-South Analysis**

Figure 8. SIDER for 2001



East-West Analysis **North-South Analysis**

Figure 9. SIDER for 2002



East-West Analysis **North-South Analysis**

Figure 10. SIDER Trend Lines for 1999 to 2002

Conclusions

The vibration testing of the bridge using the SIDER technique shows that there is very little change in the structure between its erection in 1999 through 2002. This conclusion is made by inspecting the damage index in Figure 10. The SIDER technique can be used to quickly interrogate large-scale structures in the service environment. The SIDER technique can locate areas of structural irregularity or change and can be used to computationally determine the areas where changes in structural properties exist over time.

From this result of the testing, it is concluded that the bridge has not experienced a significant change in its structural performance after four years of service. The results of the SIDER testing were able to locate some minor changes in the bridge from 1999 to 2002.

Recommendations

Additional testing on the bridge should be conducted annually to determine further changes in the overall structural performance. There is one area which has shown a change in the structural regularity. This was the only statistically significant change in the state of the bridge over the past four year time period.

The non-destructive damage detection method should continue to be developed to assess its applicability to locate damage in large-scale structures. This technique has shown promise but additional work relating the specific damage index values to the level of structural degradation would elevate this technique to a quantitative nondestructive evaluation technique.

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